ARPA-E Perspectives

Scott Hsu, Program Director, ARPA-E

Acknowledgments: Sam Wurzel (Fusion Tech-to-Market Advisor)

IFE Strategic Planning Workshop
February 22, 2022

Outline

- Introductory remarks (ARPA-E and fusion @ ARPA-E)
- Overview of ARPA-E's fusion R&D portfolio (includes 3 IFE projects)
- Remarks on IFE development via public-private partnerships

Where is ARPA-E in the DOE organizational structure?

- Secretary (S1)
  Undersecretary (S2)
  - Undersecretary for Science And Innovation (S4)
    - Office of Science (SC)
      - Fusion Energy Sciences (FES)
    - Applied Energy Offices
  - Undersecretary for Nuclear Security and NNSA (S5)
    - Defense Programs
      - Research, Development, Test, Evaluation (incl. HEDP/ICF)
  - Bunch of other orgs incl. ARPA-E

- Think of ARPA-E as "special forces" of DOE
- Funds applied R&D of limited scope/duration w/potential to transform a field and its development
- Great situational awareness on broad technology-push opportunities and market/customer needs

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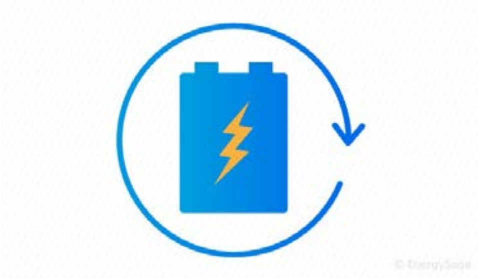
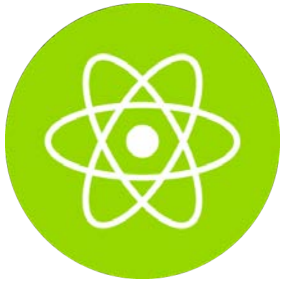
Full DOE org. chart: https://www.energy.gov/organization-chart

Framing of fusion energy within ARPA-E’s portfolio

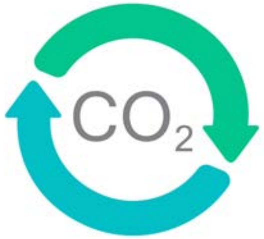
- World needs >500 EJ/year of sustainable, carbon-neutral primary energy



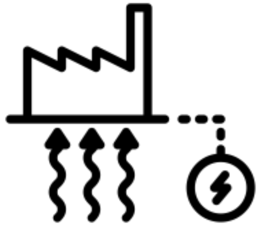
Renewables + long-duration storage



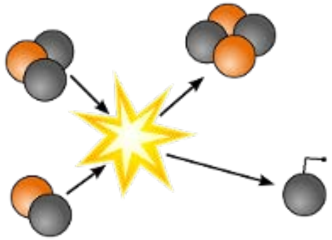
Advanced nuclear fission



Fossil fuels with carbon capture, utilization, sequestration (CCUS)



Enhanced geothermal



+ fusion?

- Unofficial view of ARPA-E fusion team:

Fusion is Plan B $\lesssim$2050 and Plan A $\gtrsim$2050.

As with all ARPA-E programs, our fusion programs are guided by market-aware, techno-economic metrics

Aspirational economic targets

Item	Cost target
Overnight capital cost (*N*th of a kind)	~\$2B, <\$5/W
LCOE	Initially < \$75/MWh Longer-term < \$50/MWh
"wall-plug gain" experiment	<\$1B, <<\$1B even better

Capex based on reports examining economics of nuclear advanced reactors.

LCOE based on ARPA-E tech-to-market (T2M) study:

Journal of Fusion Energy (2021)40:18
https://doi.org/10.1007/s10894-021-00306-4

ORIGINAL RESEARCH

Potential Early Markets for Fusion Energy

Malcolm C. Handley[1] · Daniel Slesinski[1] · Scott C. Hsu[1]

https://doi.org/10.1007/s10894-021-00306-4

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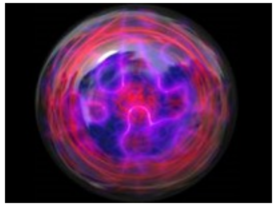
ARPA-E fusion timeline/programs (total ~$130M†)

Dr. Pat McGrath decides to pursue a fusion program

ALPHA*



Dr. Scott Hsu joins ARPA-E (Nov. 2018)

Breakthroughs Enabling THermonuclear-fusion Energy

OPEN 2021

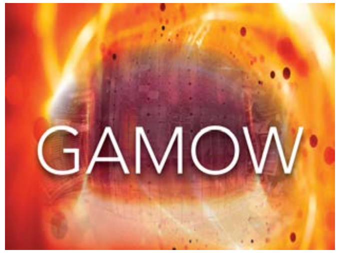
2013 — 2015 — 2018 — 2019 — 2020 — 2021

OPEN 2018

77 PROJECTS

Included 3 fusion projects

[Diagnostic "capability teams"]()



joint with SC/FES

Galvanizing Advances in Market-aligned fusion for an Overabundance of Watts

*Accelerating Low-Cost Plasma Heating and Assembly
Retrospective: https://doi.org/10.1007/s10894-019-00226-4

†includes $20M from FES on jointly funded projects

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Philosophy/vision of the BETHE (2020–2023) and GAMOW (2021–2024) programs

Aspiration: catalyze R&D trajectory toward timely commercially viable fusion demonstration.

Technical drivers

- More low-cost approaches at higher levels of fusion performance → BETHE
- Shorten the time from "wall-plug gain" to commercial pilot → GAMOW

BETHE

+ "capability teams"

GAMOW

joint with SC/FES

Programmatic drivers

- Engage larger portion of the fusion R&D community → BETHE, GAMOW
- Leverage SotA expertise/capabilities → BETHE, GAMOW
- Incentivize publicly and privately funded teams to work together → BETHE, GAMOW

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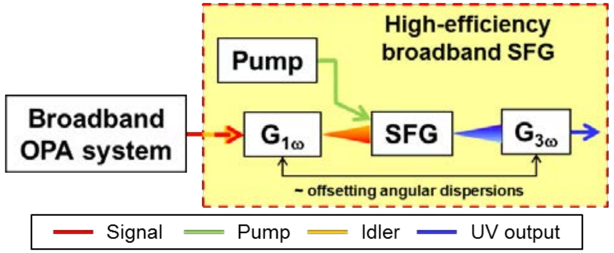
https://arpa-e.energy.gov/news-and-media/energy-briefs (episode 7)

BETHE "IFE subprogram"

Accelerate the development of next-gen, high-bandwidth, high-efficiency lasers



Innovative target design/modeling with $E_{laser} \leq 1$ MJ, G≥100 (direct drive)

Diode-pumped solid-state laser development

LABORATORY FOR LASER ENERGETICS
UNIVERSITY OF ROCHESTER

2D/3D rad-hydro and LPI modeling

Jointly funded with FES

ArF (excimer) laser development

U.S. NAVAL RESEARCH LABORATORY

Mitigation of laser-plasma instabilities (LPI)

OPEN 2021

Polymath Research Inc.

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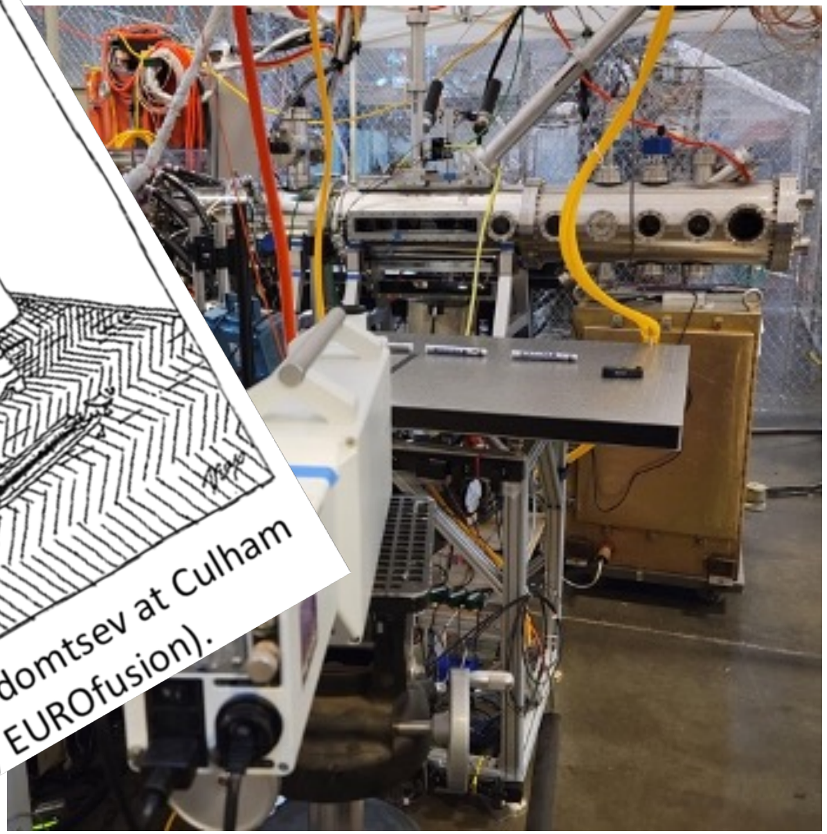
Diagnostic “capability teams” (mini-program: 2019–2022) have deployed to experiments around the country

BETHE included computational capability teams

From talk given by B.B. Kadomtsev at Culham in 1988 (courtesy EUROfusion).



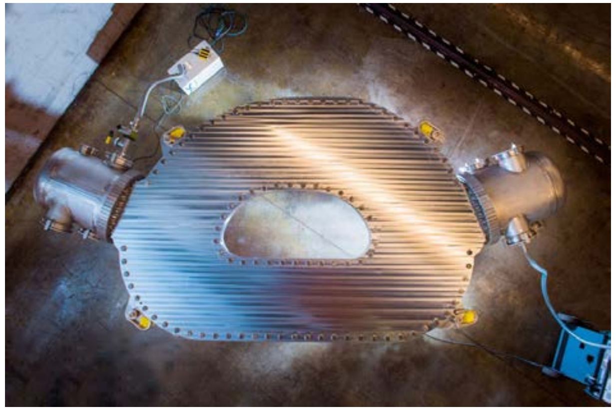
ORNL team bringing their diagnos… …ceton FRC (Princeton Fusion Systems and …).

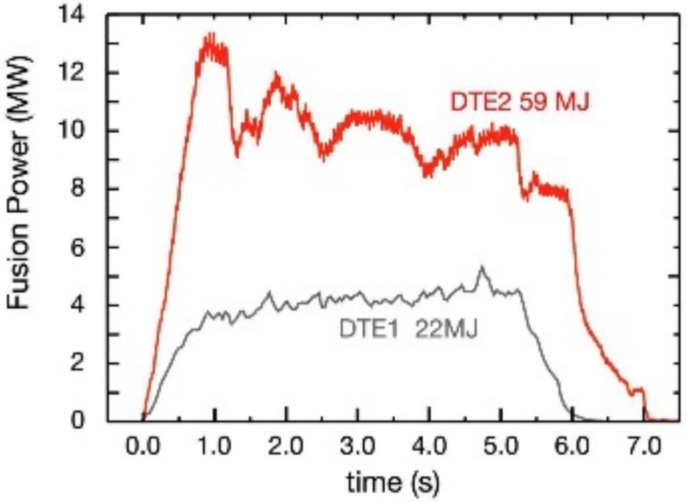
LANL and LLNL diagnostics installed on the FuZE device (Zap Energy).

https://www.arpa-e.energy.gov/news-and-media/blog-posts/fusing-further-advancement-introducing-arpa-e-fusion-capability-teams

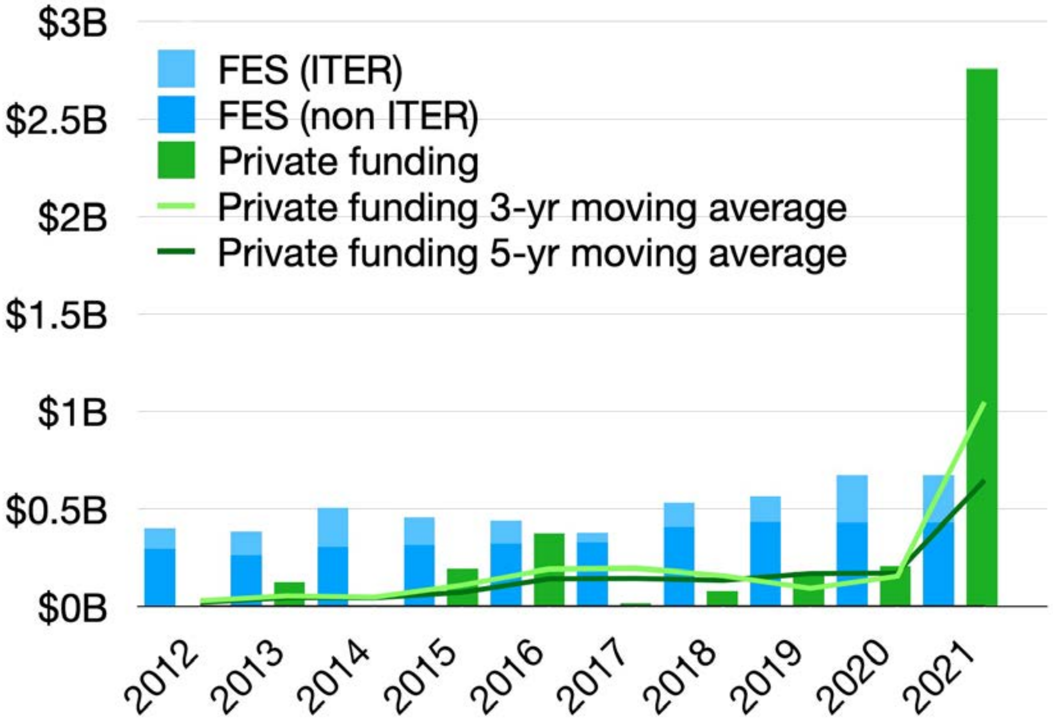
Shifting fusion landscape: major milestones and market pull

20-T magnet demonstration by Commonwealth Fusion Systems





Record fusion energy over 5-second duration (UK/EU)



Plot by Sam Wurzel, data compiled from publicly available sources.

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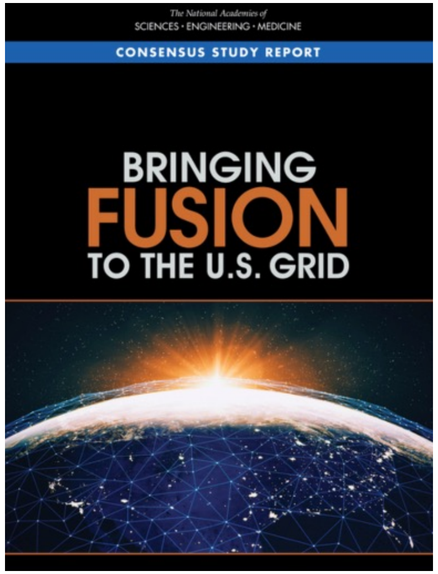
Remarks on IFE development via public-private partnerships

- Observations and lessons from MFE

- Our view of evolving investor interests

- Recommendations

Some further reading and resources

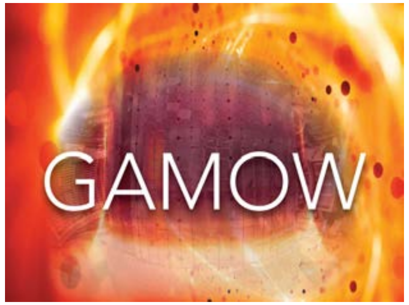


National Academies
report (2021)

Plan on Possible Cost-Share Program (2020)

NRC Fusion Public
Forums (2020–present)

BETHE Kickoff
Meeting (2020)



GAMOW Kickoff
Meeting (2021)

Join the team that is transforming the energy of tomorrow

PROGRAM DIRECTOR

- Program development
- Active project management
- Thought leadership
- Explore new technical areas

TECHNOLOGY-TO-MARKET ADVISOR

- Business development
- Technical marketing
- Techno-economic analyses
- Stakeholder outreach

FELLOW

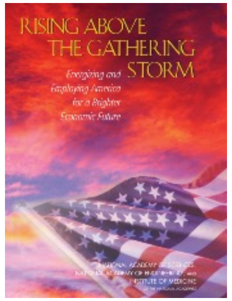
- Independent energy technology development
- Program Director support
- Organizational support

Learn more and apply: **www.arpa-e.energy.gov/jobs** or **arpa-e-jobs@hq.doe.gov**.

U.S. DEPARTMENT OF ENERGY

https://arpa-e.energy.gov

ARPA-E history and mission



2007

American Recovery & Reinvestment Act ***Signed*** – ARPA-E's first appropriations of $400 million, which funded ARPA-E's first projects

2009

1000+ Awards

FY21 Funding:
$427M

2021

Goal 1: Overcome long-term and high-risk technological barriers in the development of energy technologies that…

REDUCE IMPORTS

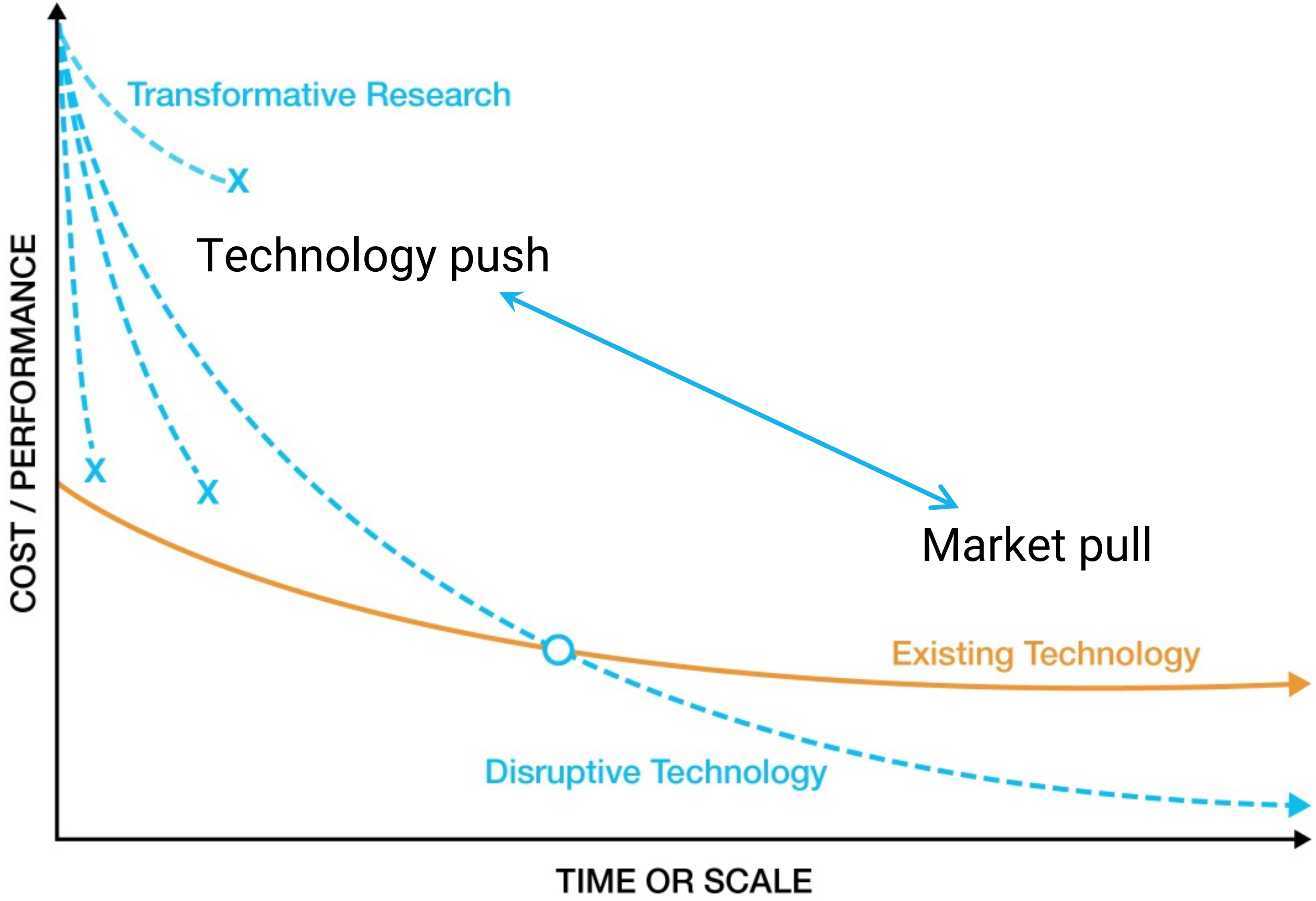
IMPROVE EFFICIENCY

REDUCE EMISSIONS

Goal 2: Ensure that the U.S. maintains a technological lead in developing and deploying advanced energy technologies.

New statutory authority on nuclear-waste management and disposition

“Changing what’s possible”



“If it works, will it matter?”

ARPA-E programs have a strong focus on tech-to-market (T2M)

SCOPE

Market insights → techno-economic metrics

MANAGE

Technical and T2M milestones

ADVISE

Dedicated T2M Advisor

PARTNERSHIPS

Connect teams with investors and other commercial stakeholders

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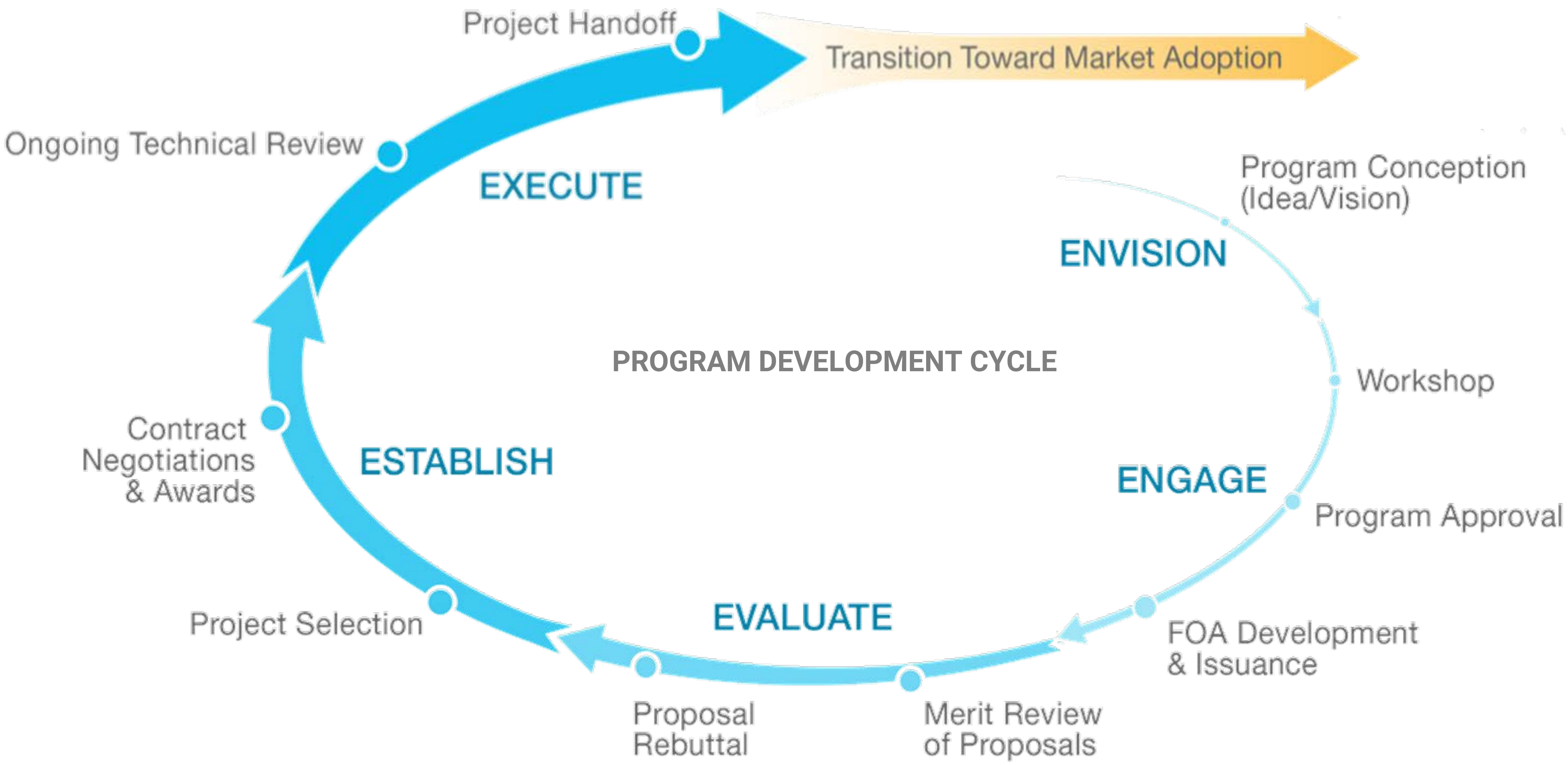
Technology-acceleration model driven by Program Directors



BETHE* program: Catalyze R&D to deliver a larger number of lower-cost fusion concepts at higher performance levels

<u>Advance the performance of lower-cost concepts</u>

<u>Lower the cost of more-mature concepts</u>

- Bring 2–3 projects to ~1 keV, and at least one to 10^{18} keV s/m^3
- Projected net-gain experiment for $\lesssim$ \$100M
- Selected projects include mirrors, spheromak, MIF, Z pinch, μ-catalyzed fusion

Concept development

Capability teams

Component technology development

- Potentially enable overnight capital cost <\$2B, <\$5/W
- Selected projects include fast-ramping tokamak HTS central solenoid, new approaches to stellarator magnets, next-gen high-bandwidth lasers for IFE

*Breakthroughs Enabling THermonuclear-fusion Energy; click [here] for program overview

GAMOW program: Accelerate R&D in fusion materials and enabling technologies to support commercially viable fusion concepts

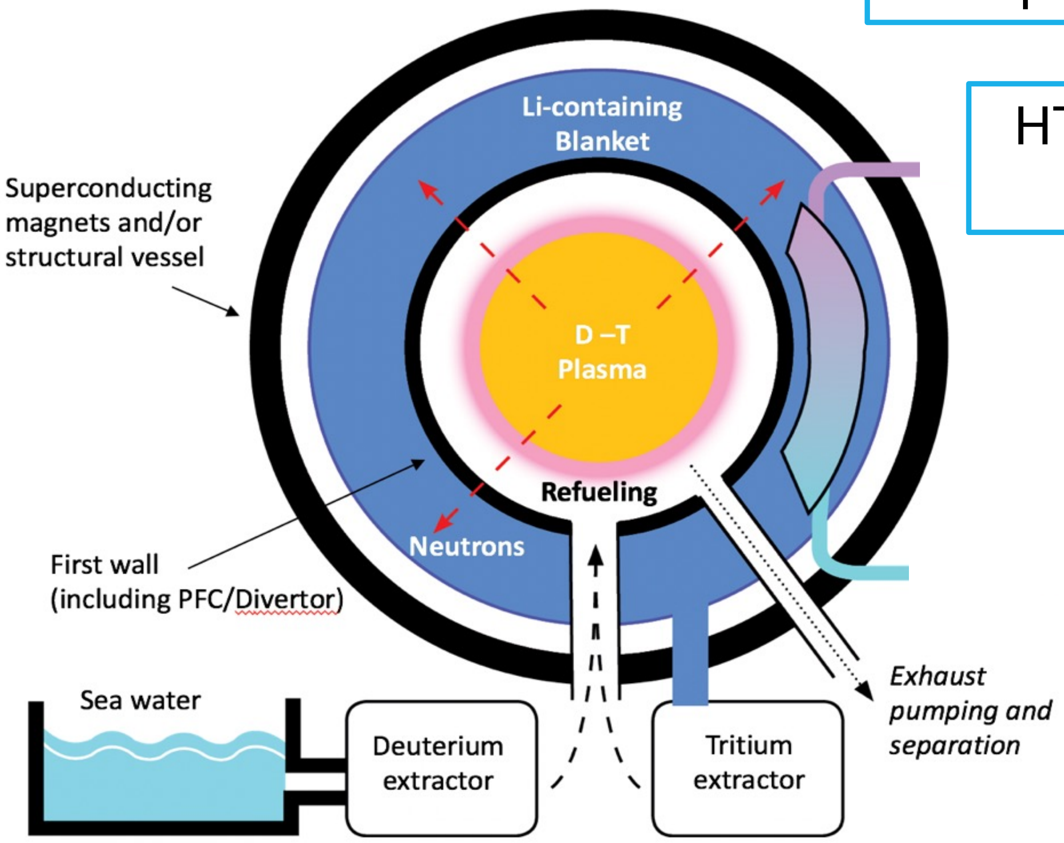
Deployable in experiments well within a decade

Device simplification or elimination of entire subsystems

Significant cost reduction

Improvements in RAMI, safety, sustainability

Joint program with SC/FES



>900-K blanket operation

HTS tape <$10/kA-m, substrate >3 GPa

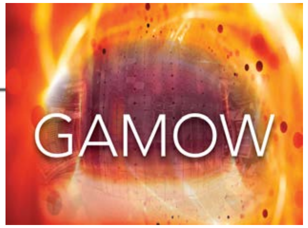
<1000-Ci (100-mg) T annual release

>10-MW/m^2 continuous power handling at 1st wall

<0.75-kG T inventory for 500-MW$_{th}$ system

Click here for program overview.

GAMOW portfolio: 14 projects across 7 technical categories



Joint program with SC/FES

Integrated first-wall and blanket modeling (ORNL)

Advanced HTS (Univ. of Houston)

Innovative PFC/divertor solutions (ORNL, UCLA)

Novel fusion materials, advanced manufacturing, testing (ORNLx2, Phoenix/Shine, Stony Brook Univ., PNNL)

Tritium extraction, pumping (SRNLx2, Colorado School of Mines)

High-efficiency electrical-driver systems (Princeton Fusion Systems, Bridge 12)

Prime recipients: 5 universities, 3 private companies, 6 national labs; click here for full list of project teams. GAMOW kickoff meeting (virtual), Jan. 21-22, 2021.

Mini-program on "capability teams": Transportable diagnostics & expert diagnosticians to support ARPA-E fusion concept teams ($7.4M)

Density, ion temp/energy

Thomson scattering

Neutron detection

X-ray detection

PPPL

UC DAVIS
UNIVERSITY OF CALIFORNIA

OAK RIDGE
National Laboratory

Lawrence Livermore National Laboratory

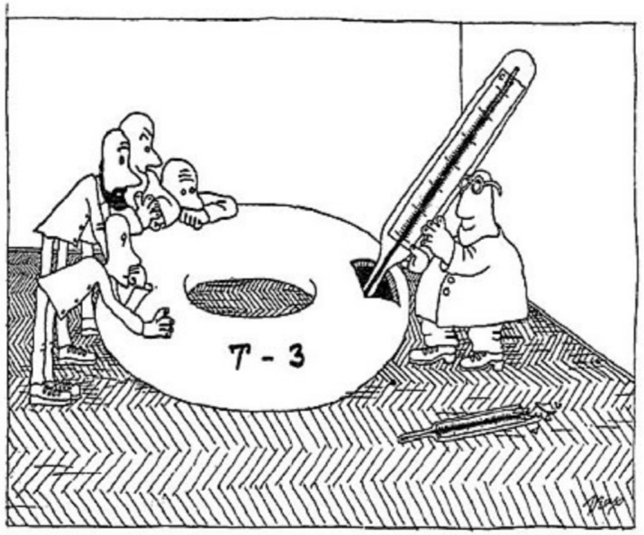
LABORATORY FOR LASER ENERGETICS
UNIVERSITY OF ROCHESTER

Lawrence Livermore National Laboratory

Los Alamos
NATIONAL LABORATORY
EST. 1943

Caltech

Magnetic "alternates"



From talk given by B.B. Kadomtsev at Culham in 1988 (courtesy EUROfusion).

Pulsed, intermediate density

Click here for full list of project teams.

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Fusion Tech-to-Market (T2M) priorities

- Investor engagement/education, e.g., review of Lawson criterion and physics progress toward energy breakeven/gain (arXiv:2105.10954) and Sam Wurzel's 2021 APS-DPP tutorial
- Fusion market studies, e.g., JFE paper on potential early markets for fusion energy
- Updated reactor-costing tool, studies, and support of concept teams, e.g., costing reports led by Woodruff Scientific
- Supporting public engagements/forums (e.g., NASEM, NRC, IAEA, other NGOs)
- Supporting/coaching our project teams (on development plans, team building, securing follow-on funding, investor pitches, etc.)

Brief summary of findings from ARPA-E fusion market study

- Most-promising early markets are high-priced electricity markets around the world (up to $110/MWh)
  - Eventually, fusion may need to cost <$50/MWh to access very large markets (to compete with natural gas w/CCS and $50/ton carbon tax)
- Load-following may not be economically feasible for fusion (it cannot afford to sit idle half the time due to large capital cost)
  - Integrated thermal storage may be needed so plant can run at high capacity factor
- Process-heat and hydrogen-production markets will be tough early markets (also, fusion may not be able to deliver heat at high-enough temperatures)
- Desalination & direct air capture alongside power generation or retrofitting coal power plants may help make fusion more economically competitive

See Malcolm Handley's talk from GAMOW kickoff, and JFE paper.

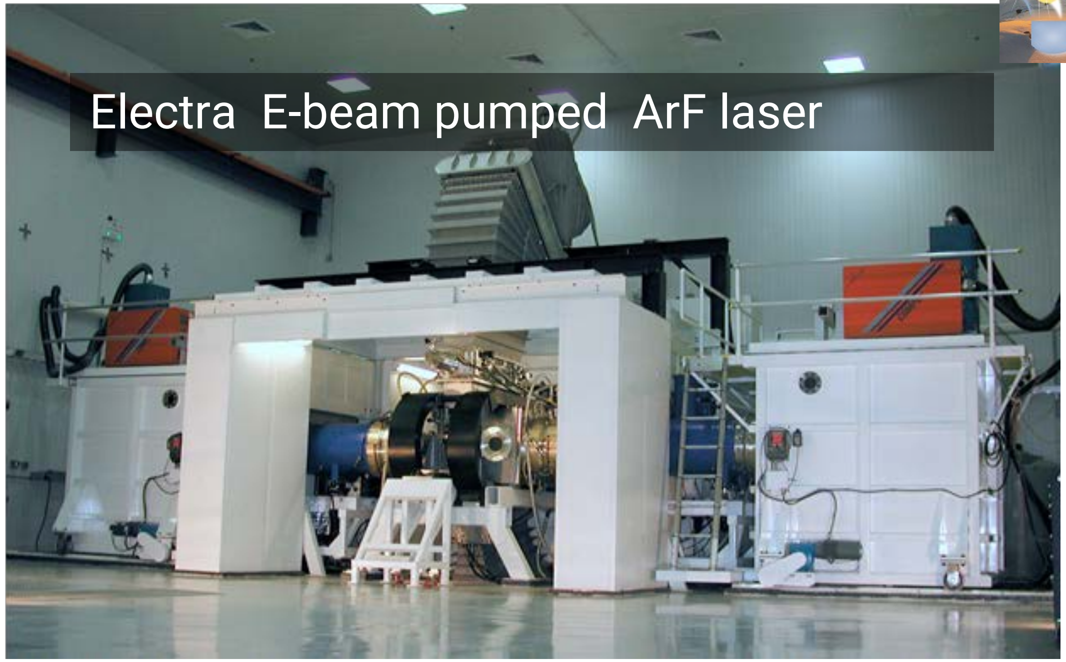
The Argon Fluoride Laser as an Enabler for Lower-Cost Inertial Fusion Energy

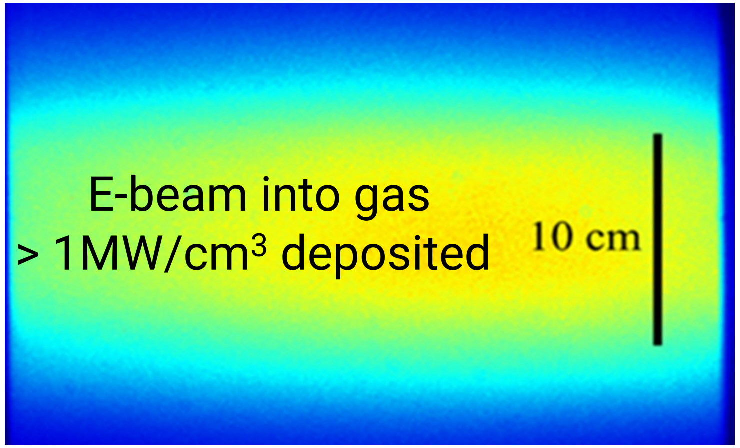
PI S. P. Obenschain, U.S. Naval Research Laboratory

- Technology Summary: The ArF laser's short wavelength (193 nm) & broad bandwidth (> 8 THz) light could potentially enable high-gain inertial fusion implosions with ≤1-MJ laser energy

- Impact: Potential to build smaller, lower-cost IFE-based power plants

- Key Project Goals:
  - Advance the basic S&T of high-energy, efficient ArF lasers
  - Develop sub-MJ, high-gain ArF direct-drive target designs

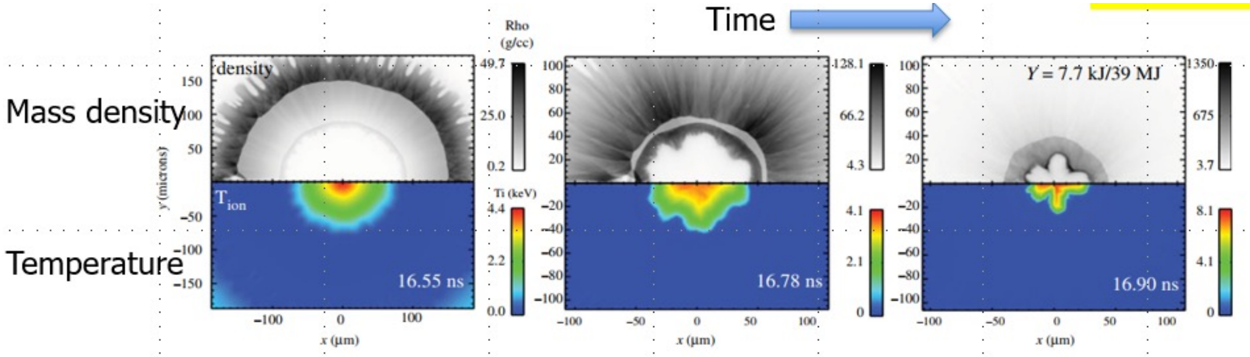




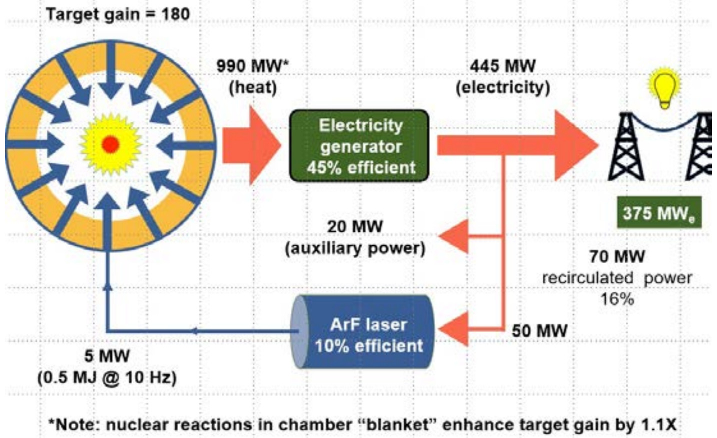
The Argon Fluoride Laser as an Enabler for Lower-Cost Inertial Fusion Energy

PI S. P. Obenschain, U.S. Naval Research Laboratory

- Early Research Highlights
  - 200 J of ArF light obtained with Electra in oscillator mode
  - Broad bandwidth (7-THz FWHM) ArF emission observed from Electra
  - Potential for gain >100 with <0.5-MJ ArF laser energy in 2D simulations



- Next Steps:
  - Demonstrate >16% ArF intrinsic efficiency on Electra (would enable 10% wall-plug efficiency)
  - Design and test efficient E-beam diode module
  - Conceptual design of efficient 30-kJ ArF amplifier to be component for a high-gain implosion facility



Power flow in a 0.5-MJ ArF IFE power plant

For more information:
https://royalsocietypublishing.org/doi/full/10.1098/rsta.2020.0031

Advanced IFE target designs with next-generation laser technologies

Valeri Goncharov, University of Rochester, LLE

Technology Summary:

- ***Develop high-gain IFE designs using new multi-color, deep UV, high-coupling-efficiency laser drivers such as broadband StarDriverTM-based technology***

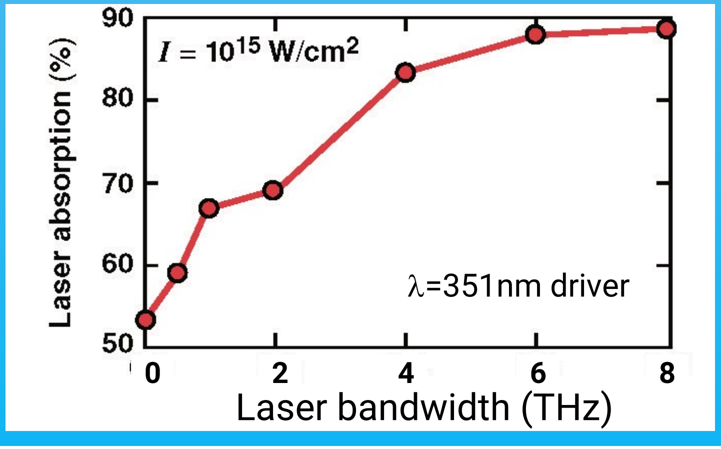
Impact:

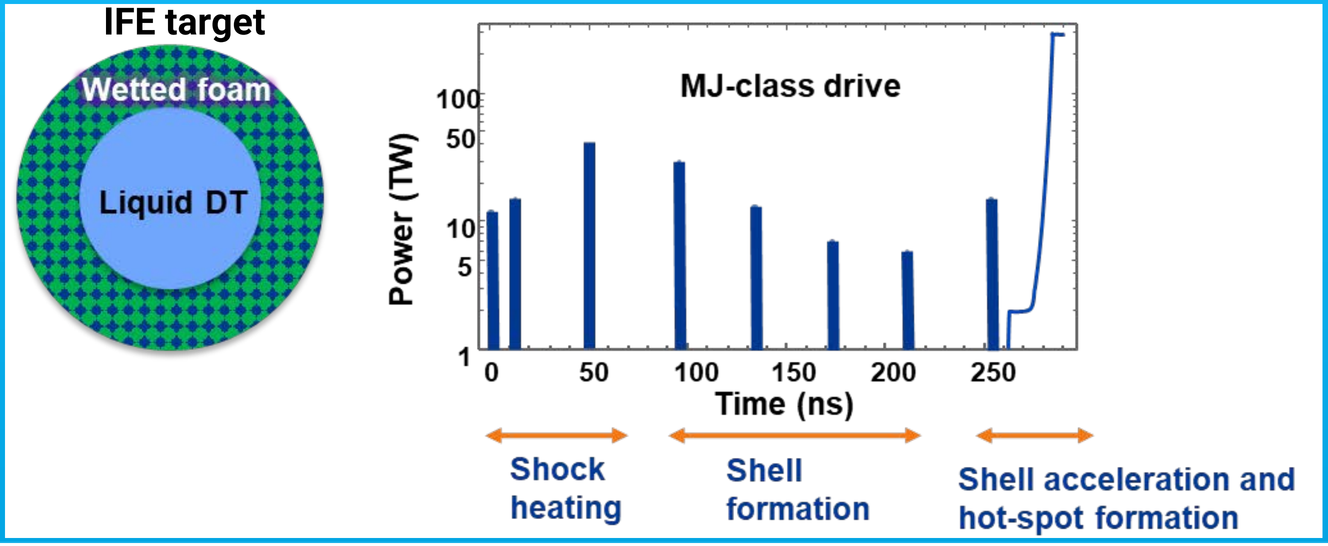
- ***Develop high-gain, robust IFE designs with mitigated losses due to laser plasma interaction processes using new laser technologies***

Key Project Goals:

- ***Demonstrate Gain >100 at laser energies E_L ~1MJ using 2D and 3D hydro simulations***
- ***Develop target concepts consistent with mass-production requirements for IFE***

Laser coupling increases with bandwidth



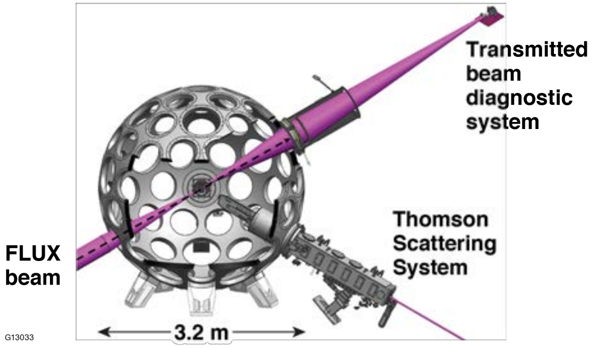


Advanced IFE target designs with next-generation laser technologies

Valeri Goncharov, University of Rochester, LLE

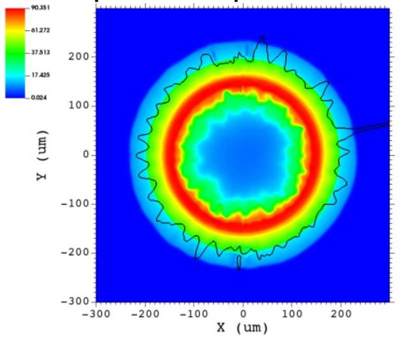
Early Research Highlights

- The fourth-generation Laser for Ultrabroadband eXperiments (FLUX) is being built on OMEGA to investigate the mitigation of LPI and beam imprint with bandwidth (1.5% at $\lambda = 351$ nm)

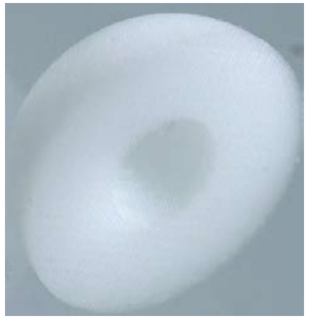


- 3-D hydrodynamic simulations show promising stability properties of the dynamic-shell concept

Shell density map at peak compression



- Advancements in additive manufacturing enabled GA and LLE to produce targets for wetted-foam ignition designs



Next Steps:

- Complete FLUX project and begin LPI experiments
- Set the requirements on the laser bandwidth for IFE plant using detailed LPI simulations
- Robustness studies of IFE target designs using 2-D and 3-D simulations
- Perform proof-of-principle experiment on OMEGA to demonstrate shell formation starting from a homogeneous-density foam target

For more information:

Publications:

1. V.N. Goncharov *et al*., Phys. Rev. Lett. **125**, 065001 (2020)
2. R. Follett *et al*., Phys. Plasmas **28**, 032103 (2021)
3. W. Trickey *et al*., *"Central Density and Low-Mode Perturbation Control of Inertial Confinement Fusion Dynamic-Shell Targets," Physics Frontiers (submitted)*

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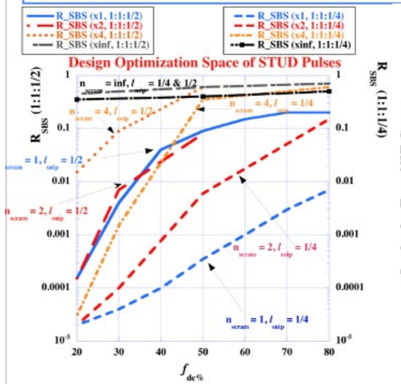
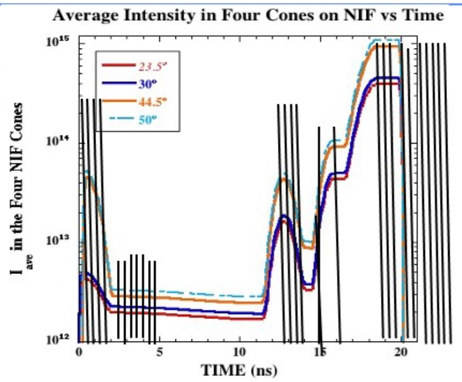
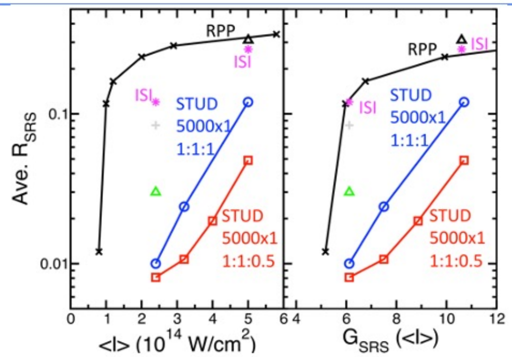
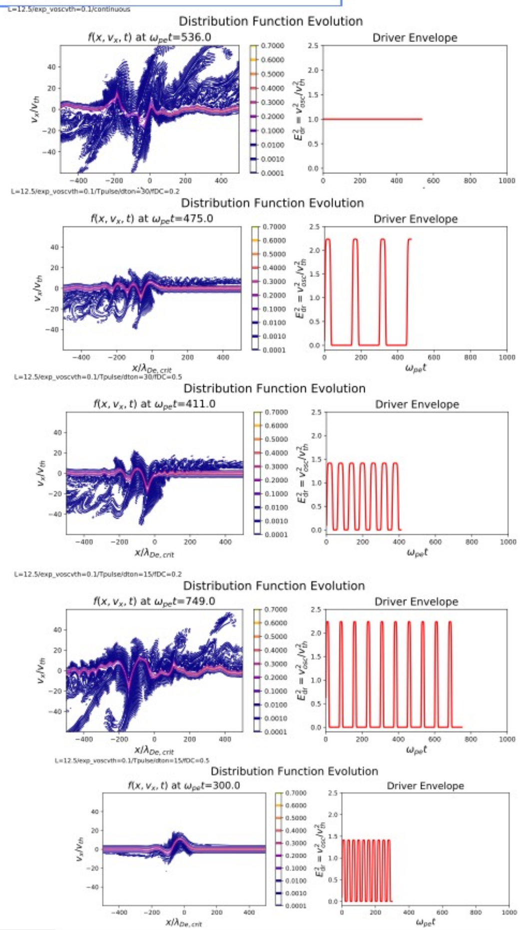
ARPA-E Funded STUD Pulse Project Highlights

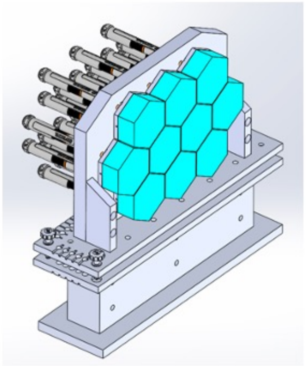
- **<u>Key STUD Pulse technology: Ferrari, Mercedes, Prius</u>**
- **Control LPI at the instability growth rate time scale. Deterministic modulations in time, scramble hot spot patterns in space. Interlace crossing beams, change speckle patterns of crossing beams in the strong coupling limit of SBS especially near mach -1.**
- **<u>Key variables:</u> T_{pulse} fixed vs I_{max} fixed, l_{snip}: Ratio of Spike duration to speckle length, f_{dc}: Duty cycle of 'on' time in one 'on' + 'off' pair, n_{scram}: Number of spikes btw speckles being scrambled**

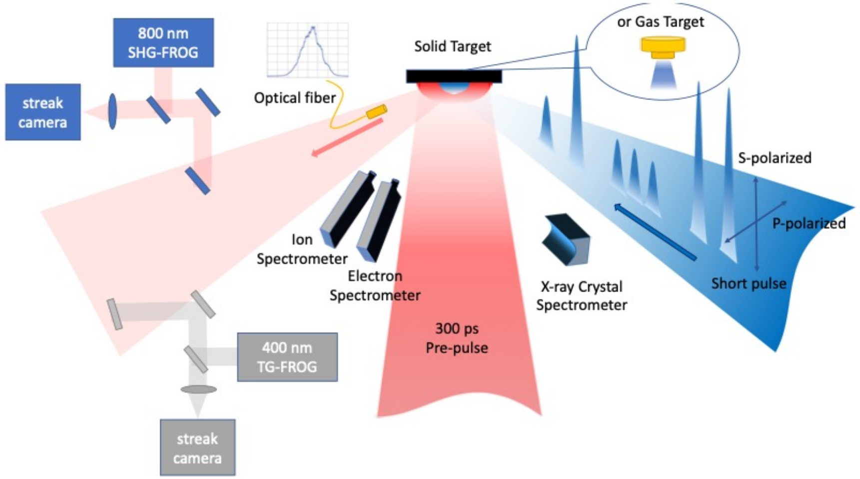












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ARPA-E Project on LPI Control Using STUD Pulses

Colorado State University

Polymath Research Inc.

- Demonstrate laboratory STUD pulse (10 spike array) performance on ALEPH at CSU using RA with 800nm and SRS with 400nm lasers
- Develop computational and theoretical models at the ODE, PDE and IDE levels for these processes controlled by STUD pulses.
- Synthesize these models into surrogate models using ML and DNN.
- Extract STUD pulse design tools based on individual models and the integration of diverse models.
- Are there universal rules? Are they interpretable? Can we design large-scale IFE experiments on JUPITER or T-STAR to test these findings?
- Can we work towards a comprehensive design tool set that solves the inverse problem for LPI for a given IFE target design?
- Give me plasma conditions as a function of space and time and target composition --> spit out a space - time sculpted STUD pulse sequence that can control LPI in that target.
- Or suggest changes to the target more favorable from an LPI point of view. Iterate.

Topics for potential future ARPA-E fusion R&D programs

- Enabling fusion with advanced fuels (i.e., aneutronic)
- Accelerating laser and target-manufacturing R&D for IFE
- Increase efficiencies of input energy and power conversion, and enable energy recapture to reduce requirements on plasma energy gain
- Fusion materials innovations, and materials by design (e.g., exploiting quantum computing/chemistry)
- Novel blanket and first-wall concepts
- Enabling co-generation applications of fusion (and coal retrofits)
- …